High resolution spectral studies and the absolute wavelength calibration of a KrF excimer laser for microlithography

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ABSTRACT

We present measurements of the spectral characteristics of a spectrally narrowed KrF excimer laser designed for use in advanced, high numerical aperture deep UV steppers. Using a specially designed high resolution grating spectrometer, we measured a bandwidth of 1.06 pm FWHM, with 95% of the energy contained within a 3.15 pm band (6W output power). Using an atomic iron emission line ($\lambda = 248.3271$ nm), the grating spectrometer, and the laser's etalon based wavemeter, the absolute wavelength was calibrated to an accuracy better than 0.1 pm.

2. INTRODUCTION

For the fabrication of sub -0.4 m design rule IC devices, advanced excimer steppers being introduced now have NA's greater than 0.5 with field sizes exceeding 20 x 20 mm^2. As a consequence, the excimer laser for these steppers are required to have a very narrow and tight spectral distribution, along with an extremely stable center wavelength. For example, the spectral FWHM bandwidth specification may be ≤ 1.2 pm, with the additional requirement that 95% of the total integrated energy be confined within a ≤3.5 pm band. Similarly, the center wavelength is required to be stable to better than ± 0.1 pm short term and ± 0.25 pm long term. Short term wavelength instabilities, i.e. over a burst of 25 - 50 pulses, spread the integrated energy spectrum during an exposure sequence, effectively broadening the linewidth. Longer term wavelength drift, over an 8 to 24 hour period, affects the focal plane stability.

In developing a laser to meet such stringent requirements, an important arena of technology is metrology: How does one measure the spectral profile and the background energy distribution for such a narrow band laser? Similarly, what instrument has the capability of measuring the absolute laser wavelength and its stability to ± 0.1 pm? At present, no commercial spectrometer or absolute wavelength calibration system exists that can meet these requirements.

3. HIGH RESOLUTION SPECTRAL STUDIES

3.1 Instrumentation

The high resolution grating spectrometer used in this study (Fig. 1) is a redesigned and improved version based on one reported previously [1]. An echelle grating with a high angle of incidence is used in a near-Littrow configuration, producing a theoretical resolving power = 1.4×10^6 , or 0.18 pm at 248 nm. The free spectral range is 5 nm. The spectrum is scanned in the output image plane by a slit and photomultiplier combination mounted on a stepper motor-controlled translation stage. One scan step corresponds to 0.005 pm, providing very accurate, continuous readings. The input light is introduced into the spectrometer with a fiber optic bundle which

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provides uniform and consistent illumination of the entrance slit and the internal optics in the spectrometer. Because of the extremely high dispersion in the focal plane, the working scanning range is ± 30 pm around the central wavelength. Coarse tuning (to within 5 pm of line center) is accomplished by rotating the grating directly. Careful control of the height and rotational angle of the exit slit is necessary to achieve maximum resolution.

The operating system is based on the Macintosh computer and provides control for the stepper motor and data acquisition for the photomultiplier signal, in sync with laser operation. We used a special optical arrangement (Fig. 2) to directly measure the real resolution of the spectrometer. Very narrow-band light was produced by transmitting the laser light through two etalons. One has a free spectral range (FSR) = 20 pm and a finesse (F) = 100; the second has an FSR = 2 pm and F = 100. Fine adjustment of these etalons provides output light with $\Delta \lambda = 0.02$ pm, which is an order of magnitude less than the theoretical spectrometer resolution. The measured instrument function of the grating spectrometer using this light source is shown in Fig 3. The resolution proved to be 0.22 pm FWHM, which is very close to theoretical value.

3.2 Noise Levels

A good understanding of background optical noise levels (due to scattering within the spectrometer), and electronic offsets (within the data acquisition system) is necessary in order to accurately compute the spectrally integrated energy (i.e. 95% energy bandwidth). A typical spectrum is shown in Fig. 4, taken while the laser was operating at 500 Hz and 12 mJ. The vertical scale is shown greatly expanded to examine the tails of the spectrum. The maximum signal is 3 V, which is within the linear response range of the photomultiplier. The electronic offset for our system is typically 14 mV, easily determined by closing the laser shutter and taking a scan. The optical noise level due to all scattering/leakage sources within the spectrometer excluding the grating is 2×10^{-5}, determined by blocking the grating with a black screen (Figure 4, grating blocked).

The most difficult noise level to determine is that due to uniform scattering from the grating itself and from other optics on the way to the photomultiplier. This scattering could be responsible for some or all of the 1.5×10^{-4} level of the spectral wings seen in figure 4. Is this level a real broadband tail to the laser spectrum, or is it an artifact of the spectrometer? In the next section, we present a technique for setting an upper bound on the magnitude of the real spectral tails.

3.3 Intensity in the Spectral wings.

We investigated the intensity of the light in the spectral tails using the arrangement shown in Fig. 6. The idea of this method is to decrease the total amount of the light inside the spectrometer (and therefor decrease the optical scattering) without decreasing the spectral intensity in the weak wings. We used an etalon (FSR = 20 pm, F = 30) to selectively stop the central spectral peak and to pass, unattenuated, energy in the wings spaced ± 10 pm from the center. The theoretical contrast of this modulation is 365. The etalon with was tuned to minimum transmittance for the central laser wavelength (see figure 7). A diffuser is used to provide a spectrally uniform attenuation of the input light intensity (to regulate signal level) and to measure the actual peak

transmittance of the etalon. We didn't see any increase in the intensity of the light in the expected bands (figure 7) to a sensitivity of 10^{-4}, which after correction for etalon transmittance gives a detection limit of 5×10^{-6}. This shows that virtually all of the intensity in the spectral wings at ± 10 pm from laser center is due to scattering from the grating and other internal optics.

Figure 5 shows the normalized laser spectrum and spectral energy integral. The FWHM is 1.06 pm and integration of the spectrum over ± 25 pm range (not fully shown in figure 5) shows that 95% of the energy is within 3.15 pm. These figures represent the convolved laser spectrum, which includes the broadening effects of the spectrometer's finite resolution. We present spectral data in convolved form because it gives conservative upper limits for the results, and eliminates the uncertainties which can occur when one attempts to deconvolve the data. In any event, the high resolution of the spectrometer produces relatively small errors in the FWHM, and even smaller errors in the integrated parameters. In addition, the energy integral of figure 5 uses a spectrum for which the baseline is corrected only by the 'grating blocked' level (figure 4). A more aggressive baseline subtraction which sets the spectral tails to true zero at ±25 pm from center decreases the width of the 95% energy integral by 0.2 pm, and for the 90% energy integral by 0.1 pm.

4. ABSOLUTE WAVELENGTH CALIBRATION

For absolute wavelength calibration of the laser, we use an iron hollow cathode lamp which produces a fairly intense reference line at 248.3271 nm. The lamp uses neon as the buffer gas, and is operated at 20 mA current. The emission line is Doppler broadened, and assuming a plasma temperature of 1000°K, should exhibit a Gaussian lineshape with a bandwidth of 0.75 pm FWHM. Measurement of this line with the spectrometer directly gives a convolved value $\Delta \approx 0.85$ pm. After deconvolution, the estimated width decreases to $\Delta = 0.76$ pm, in very good agreement with theory. As reported previously[1], the laser spectrum and reference lamp are folded together into the same optical fiber, and a scan is taken. Electronics separate the pulsed laser signal from the continuous reference lamp. A good, symmetrical spectral profile allows one to measure the position of the laser line center with respect to the reference lamp with an accuracy better than 0.08 pm.

5. SUMMARY

In summary, this is the first in-depth study of the spectral characteristics of an extremely line narrowed excimer laser for microlithography. Such a study is critical to the design of advanced deep UV stepper lenses and it provides a means to specify the laser spectrum unambiguously.

6. REFERENCES

1. R. Sandstrom, 'Measurements of Beam Characteristics Relevant to DUV Microlithography on a KrF excimer Laser', presented at the 1990 SPIE Symposium on Microlithography, paper 1264-37.

7 LIST OF FIGURES

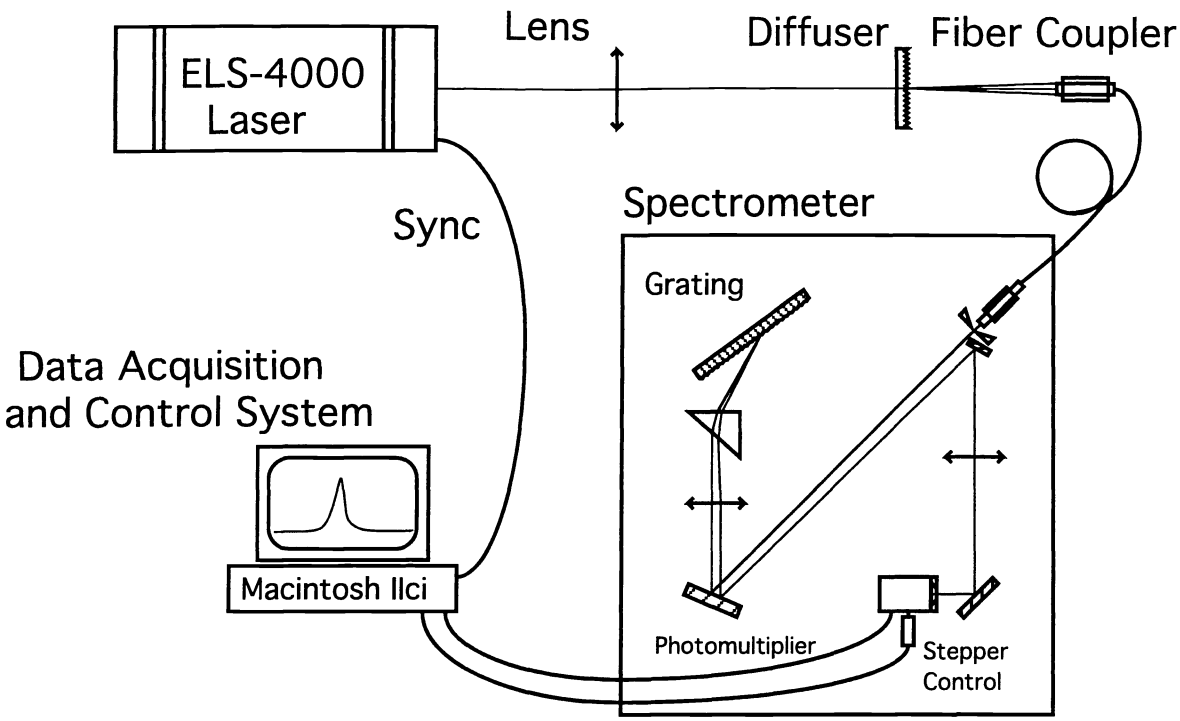

Fig.1 High Resolution Grating Spectrometer Layout.

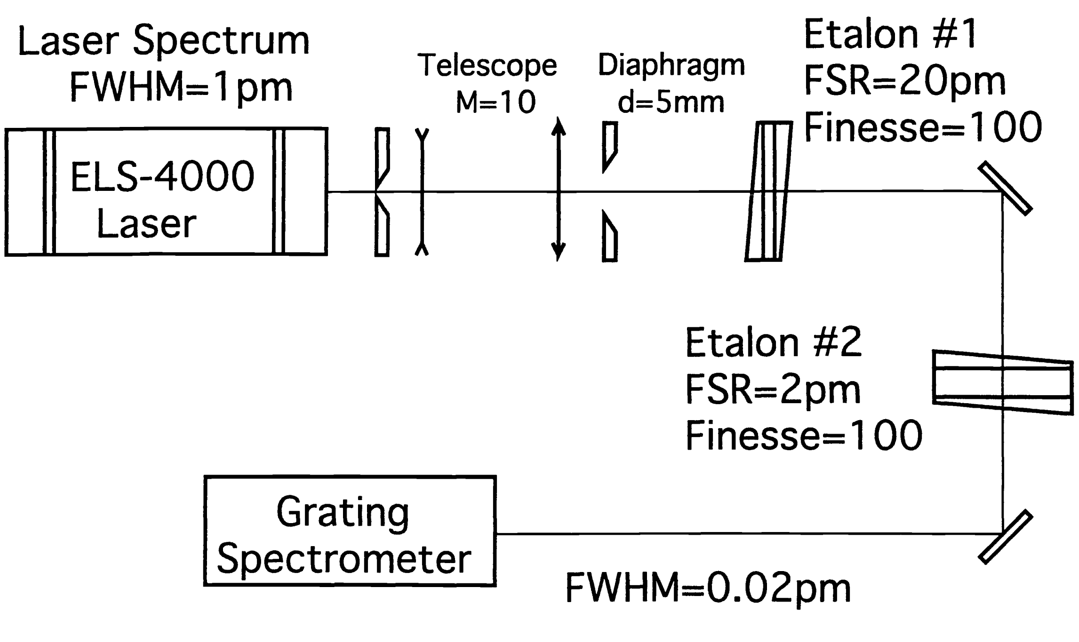

Fig.2 Optical arrangment to provide light source with Bandwidth=0.02pm to measure Spectrometer Resolution

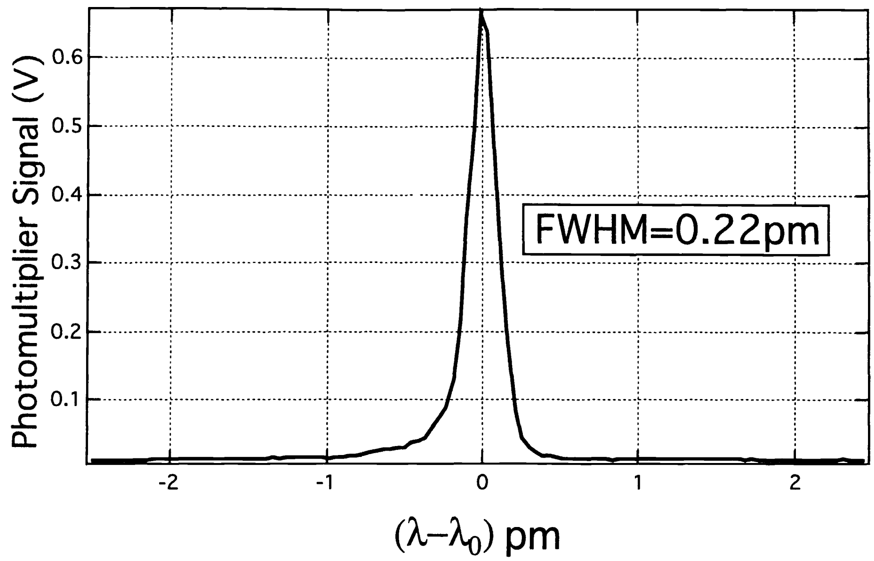

Fig.3 High Resolution Grating Spectrometer Measured Slit Function. Echelle Grating: Theoretical Resolution= 0.18pm Light Source Width=0.02pm

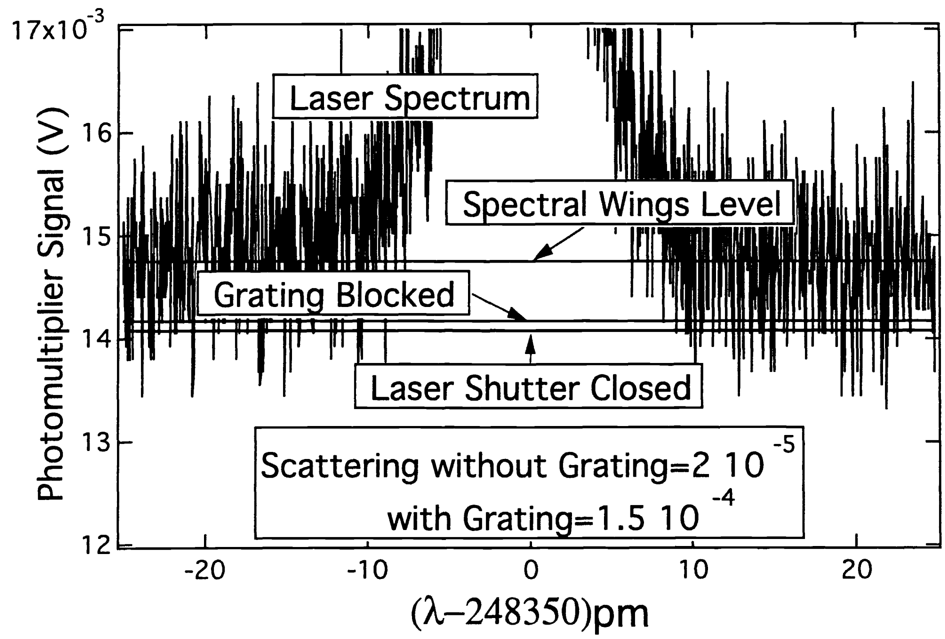

Fig.4 Laser Spectrum and Typical Electronic Bias and Internal Optical Noise Level

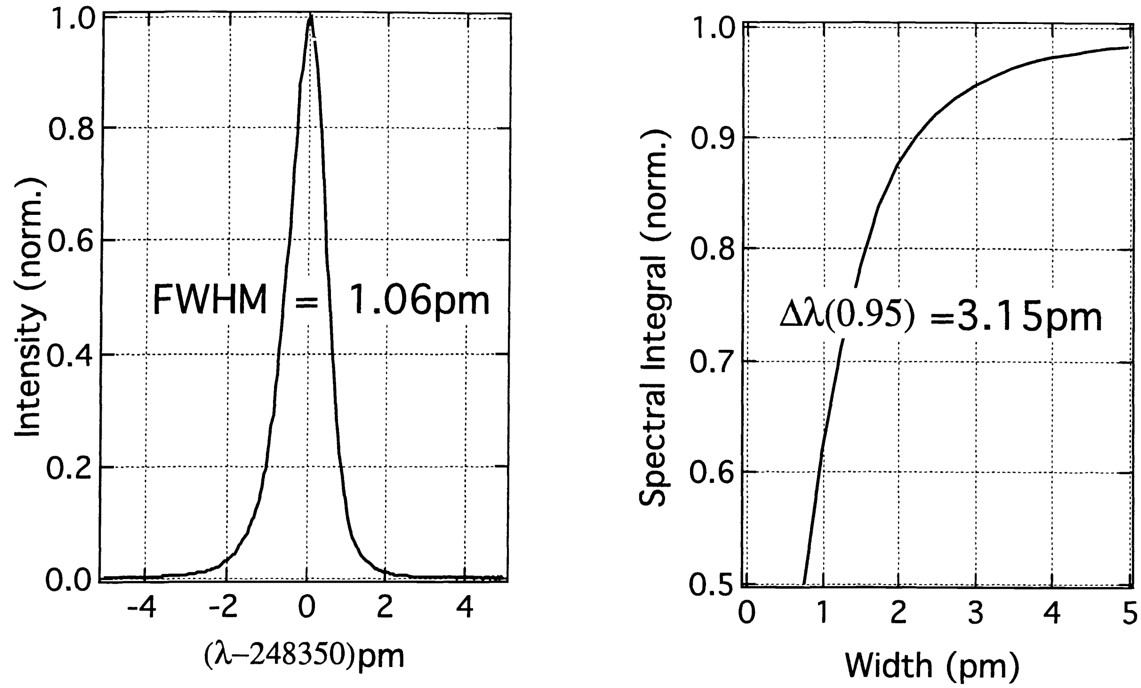

Fig.5 Laser Spectrum and Spectral Energy Integral

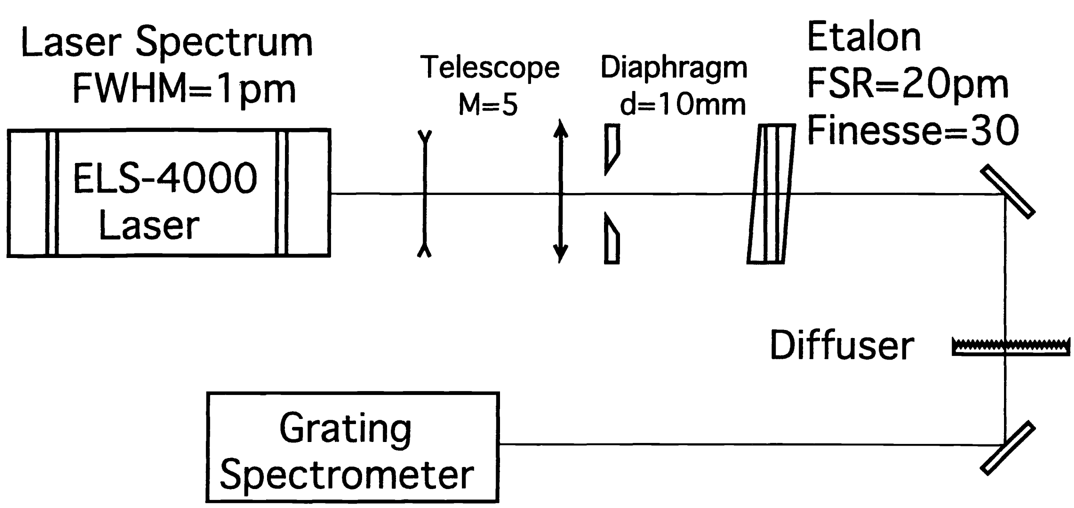

Fig.6 Optical arrangement to measure Light Intensity in Spectral Wings. Etalon Transmittance=0.02, Diffuser Transmittahce=0.02.

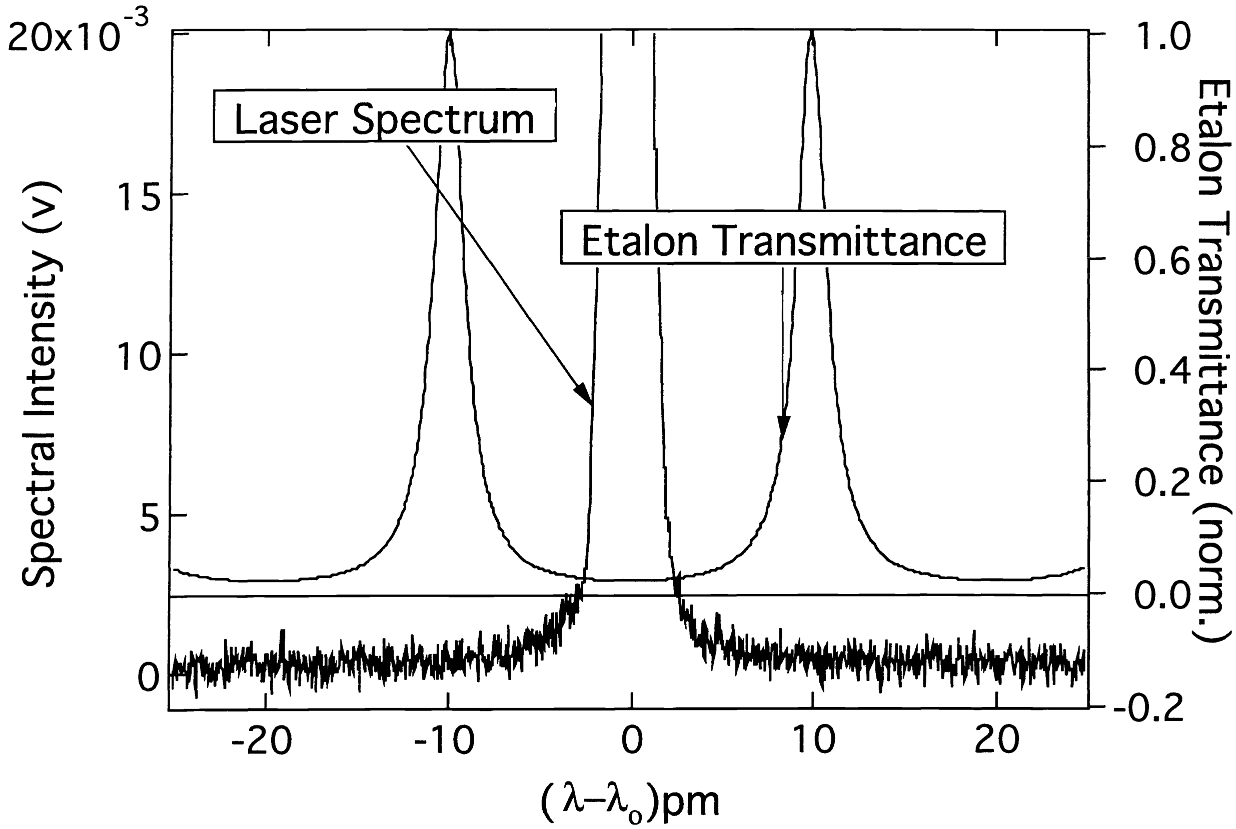

Fig.7 Laser Spectrum Modulated with Etalon Transmittance Function. Measured Depth of Modulation=50 and Detection Limit 5 ppm.